Renewable and Sustainable Energy Reviews 14 (2010) 3237–3241

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Effects of meteorological variables on exergetic efficiency of wind turbine power plants

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ARTICLE INFO

Article history:
Received 24 May 2010
Accepted 2 June 2010

Keywords:
Exergy efficiency
Meteorological variables
Wind energy
Renewable energy

ABSTRACT

This present paper deals with exergy efficiency results of the Wind Turbine Power Plants (WTPPs). Effects of meteorological variables such as air density, pressure difference between state points, humidity, and ambient temperature on exergy efficiency are discussed in a satisfactory way. Some key parameters are given monthly for the three turbines. Exergy efficiency differs from 0.23 to 0.27 while temperature is changing from 268.15 K to 308.15 K with air density 1.368–1.146 (kg/m^3). While pressure difference (ΔP) between inlet and outlet of the turbine differs from 100 to 1100 (Pa), exergy efficiency decreases fairly for different wind speeds. While specific humidity is changing from 0.001 to 0.015 ($kg_{water}/kg_{dry\ air}$), exergy efficiency decreases gently. Generally these meteorological variables are neglected while planning WTPPs, but this neglect can cause important errors in calculations and energy plans. Obtained results indicate that while planning WTPPs meteorological variables must be taken into account.

Contents

1. Introduction

1.1. A brief review of current status of WTPPs

Wind power is the conversion of wind energy into a useful form such as electricity using wind turbines. At the end of 2008, worldwide installed capacity of wind-powered generators was 121.2 GW. Although wind produces only about 1.5% of worldwide electricity use, it is growing rapidly having doubled in the three years between 2005 and 2008. It has achieved relatively high levels of penetration accounting for approximately 19% of electricity production in Denmark, 11% in Spain and Portugal, and 7% in Germany and the Republic of Ireland in 2008 [1].

For Turkey, electricity consumption is rising about 9 per cent a year and this is increasing each year. Turkey imports around 70% of its cumulative energy needs [2]. In Turkey, electricity generation through wind energy for general use was first realized in 1986 with a 55 kW nominal wind energy capacity in Izmir. Utilization of wind

Abbreviations: WTPP, Wind Turbine Power Plant; TSMS, Turkish State Meteorological Service.

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doi:10.1016/j.rser.2010.06.002

Nomenclature

A	rotor swept area (m^2)
$C_{p,a}$	air specific heat (kJ/kg K)
$C_{p,v}$	water vapor specific heat (kJ/kg K)
Ex_{dest}	exergy destruction (W, kW)
$\dot{m}$	mass flow rate of air (kg/s)
$\dot{m}_w$	mass flow rate of water vapor in air (kg/s)
P	pressure (kPa)
P_0	average pressure (kPa)
ΔP	pressure difference between inlet and outlet of the turbine (Pa, kPa)
R_a	gas constant (kJ/kg K)
R_v	vapor constant (kJ/kg K)
T	temperature (K)
T_0	reference temperature (K)
V_r	local wind velocity (m/s)
W_a	available power (W)
W_e	power at inverter output (W, kW)
W_u	useful power from turbine (W, kW)
L_{ex}	exergy loss (kW)
Greek letters	
ω	humidity ratio (kg(water)/kg(air))
ω_0	humidity ratio at reference point (kg(water)/kg(air))
ε	exergy efficiency(-)
ψ_a	specific exergy of air (kJ/kg)
ρ	air density (kg/m^3)

energy in Turkey has increased since 1998 when the first wind power plant (1.5 MW) was installed in Çeşme-Izmir. By the end of 2008 seventeen wind power plants were installed with a total capacity of 433.35 MW. By the end of 2009 it is expected to be around 850 MW by the new ones. In Turkey, only 0.3% of electricity production is provided by wind turbines [3,4].

1.2. Exergetic studies on wind turbine power systems

The exergy analysis is a vital tool for all energy resource utilization since exergy is a part of the energy analysis. The theory of exergy analysis is basically that of available energy analysis. The concepts of exergy, available energy, and availability are essentially similar. The concepts of exergy destruction, exergy consumption, irreversibility, and lost work are also essentially similar. Exergy is a measure of the maximum useful work that can be done by a system interacting with an environment, which is at a constant pressure P_0 and a temperature T_0 [5].

Modern wind turbines range from around 600–5 MW of rated power, although turbines with rated output of 1.5–3 MW have become the most common for commercial use; the power output of a turbine is a function of the cube of the wind speed, so as wind speed increases, power output increases dramatically [1]. Areas where winds are stronger and more constant, such as offshore and high altitude sites, are preferred locations for wind farms. Landowner and community support, feasible permitting, compatible land use, nearby access to an appropriate electrical interconnect point, appropriate site conditions for access during construction and operations, aviation compatibility, favorable electricity market are the most common facts those are taken into account while planning a wind land. As we conclude in this paper meteorological variables play important role for efficiency of the turbine. The most effective meteorological variables as temperature, pressure and moisture play important roles in wind occurrence. Generally, in wind engineering, moisture changeability is negligible and air is assumed to be in a dry condition. This situation can cause important errors in calculations and energy plans [6].

Ozgener and Ozgener [7], Ozgener et al. [8] performed a case study; exergy and exergoeconomic analysis of a wind turbine system (1.5 kW) located in Solar Energy Institute of Ege University, Izmir, Turkey. They reported that exergy efficiency changed between 0% and 48.7% at different wind speeds according to a dead state temperature of 293.15 K and an atmospheric pressure of 101.325 kPa considering pressure differences between state points. Considering temperature differences between state points exergy efficiencies were calculated to be 0–89% [7].

Rosen et al. [6] studied recently developing a new sustainability index as a measure of how exergy efficiency affects sustainable development. Comparing exergy efficiency and energy efficiency graphs, they conclude that exergy efficiency is more reliable than energy efficiency because of the smoothness of the graph. They took the role of exergy in increasing efficiency and sustainability and reducing environmental impact as subject, and they reached that result: exergy can identify better than energy the environmental benefits and economics of energy technologies. The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints [6]. Koroneos et al. [9] applied exergy analysis to renewable energy sources including wind power. But in this paper only the electricity generation of wind turbines is taken into account. They concluded that while the wind speed changes between 5 m/s and 9 m/s, exergy efficiency changes between 35% and 45%. Exergy lost in rotor mostly. Jia et al. [10] carried out an exergy analysis of wind energy. They considered wind power for air compression systems operating over specified pressure differences, and estimated the system exergy efficiency.

Ahmadi and Ehyaei [11] studied exergy analysis recently on Bergey Excel-S type wind turbine. Modelling entropy production, they concluded that entropy production is directly opposite of energy production, also they revealed that exergy analysis is more powerful than energy analysis for energy systems [11].

The efficiency results of the system are presented for the last two years. Using exergetic parameters several key variables have been evaluated, including exergetic efficiencies. In this paper, we investigate the performance characteristics of the Turkey's first installed (1998) wind plant (1.50 MW) in Çeşme-Izmir, and we present an overview of these results for the period 2007–2008 operating seasons.

The effects of temperature, humidity, density, etc. should always be taken into account when planning wind farms. There is abundant literature and reports on the effect of these parameters on power performance and these effects are well described in the IEC 61400-12-1 [12]. To the best of the authors' knowledge, no any examination of the long term (11 months) exergetic efficiencies have been analyzed. In addition, the originality of this paper as follows: the effects of these variables on exergetic efficiency will be given clearly, and results indicate that not only wind speed but also meteorological variables affect the exergetic efficiency of wind turbines.

2. Case study

Selected Wind Turbine Power Plant (WTPP) field is located in village Germiyan-Çeşme 86 km far from Izmir. Evaluated WTPP is Turkey's first installed (1998) wind plant (1.50 MW). Measured average wind speed around the hub is 10 m/s in 2007/2008

operating season. Height of hub is 42 m. Turbine type is Enercon E-40. Rotor diameter is 40.3 m. The turbines have three blades, the blade length is 20 m, cut in velocity is 2.5 m/s and cut off velocity is 25 m/s. Power plant has been working since February 1998 and it produces around 5,000,000 kW h each year [13]. In this study, the reference state was considered varying from 281.55 K to 299.75 K and the state of environment at which the temperature and the atmospheric pressure are 293.15 K and 101.325 kPa, respectively meteorological data were taken from Turkish State Meteorological Service (TSMS) [14].

3. Analysis

3.1. Exergy analysis

The wind speed is the key driver for wind energy systems in the form of kinetic energy. The exergy content of the blowing air simply equals the kinetic energy as

$$\text{Exergy of kinetic energy} = \text{availability} = k \cdot e_1 = \frac{V_r^2}{2} \tag{1}$$

To determine the available power, we need to know the amount of air passing through the rotor of the windmill per unit time, the mass flow rate. Taking average ambient conditions (293.15 K and 101.325 kPa) in this study the density of air is 1.225 kg/m^3 and its mass flow rate is:

$$\dot{m} = \rho \cdot A \cdot V_r = \rho \cdot \pi \cdot R^2 \cdot V_r \tag{2}$$

$$\text{Available power} = W_a = \dot{m} \cdot k \cdot e_1 \tag{3}$$

It can be defined as the maximum available power to the windmill. Most windmills in operation today harness about 20–40% of kinetic energy of the wind. Kinetic exergy is a form of mechanical energy, and thus it may be converted to work entirely. Therefore, the work potential or exergy of kinetic energy of a system is equal to the kinetic energy itself, regardless of temperature and pressure of the environment [15].

Exergy is always evaluated with respect to a reference environment (the so-called dead state). In analysis, the temperature T_0 and pressure P_0 of the environment are often taken as standard-state values, such as 1 atm and 25 °C. However, the reference environment conditions may be specified differently, depending on the application. T_0 and P_0 may commonly be taken as the average ambient temperature and pressure, respectively, for the location at which the system under consideration operates or if the system uses atmospheric air. T_0 might be specified as the average air temperature if both air and water from the natural surroundings were used. T_0 would be specified as the lower of the average temperatures for air and water [16]. Exergy efficiency, useful work (W_u) and exergy destruction (losses) can be calculated by using the Eqs. (4)–(10), respectively. The exergetic efficiency of a turbine is defined as a measure of how well the stream exergy of the fluid is converted into inverter work output. Applying this to the wind turbines, we obtain exergy efficiency as [7]

$$\varepsilon = \frac{W_e}{W_u} = \frac{W_e}{\dot{E}x_1 - \dot{E}x_2} \tag{4}$$

where the useful work is

$$W_u = (P_1 - P_2) \cdot \frac{\dot{m}}{\rho} \tag{5}$$

The exergy losses are defined as

$$\dot{E}x_{dest} = L_{ex} = W_u - W_e = (\dot{E}x_1 - \dot{E}x_2) - W_e \tag{6}$$

Here, the flow exergy rate (Ex) is

$$\dot{E}x = \dot{m} \cdot \psi_a \tag{7}$$

The specific exergy of humid air is calculated from equations (8) and (9) [17,18]

$$\begin{aligned}\psi_a = {} & (C_{p,a} + \omega C_{p,v}) T_0 \left[\frac{T}{T_0} - 1 - \ln\left(\frac{T}{T_0}\right)\right] \\ & + (1 + 1.6078\omega) R_a T_0 \ln\left(\frac{P}{P_0}\right) \\ & + R_a T_0 \left\{(1 + 1.6078\omega) \ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega}\right)\right. \\ & \left. + 1.6078\omega \ln\left(\frac{\omega}{\omega_0}\right)\right\}\end{aligned} \tag{8}$$

and

$$\begin{aligned}\psi_a = {} & (C_{p,a} + \omega C_{p,v})(T - T_0) \\ & - T_0 \left[(C_{p,a} + \omega C_{p,v}) \ln\left(\frac{T}{T_0}\right) - (R_a + \omega R_v) \ln\left(\frac{P}{P_0}\right)\right] \\ & + T_0 \left[(R_a + \omega R_v) \ln\left(\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega}\right) + 1.6078\omega R_a \ln\left(\frac{\omega}{\omega_0}\right)\right]\end{aligned} \tag{9}$$

where the specific humidity ratio is

$$\omega = \frac{\dot{m}_v}{\dot{m}} \tag{10}$$

and T_0, P_0 are reference temperature and atmospheric pressure that are 293.15 K and 101.325 kPa in this study, respectively.

3.2. Assumptions

In this study, we assumed that $C_{p,a}$, $C_{p,v}$ are equal to 1.004 kJ/kg K, 1.861 kJ/kg K, respectively. Gas constant R_a, water vapor constant R_v are assumed to be 0.287 kJ/kg K and 0.4615 kJ/kg K, respectively. Furthermore, reference state environment pressure P_0 and reference state temperature T_0 are taken as 101.325 kPa, 293.15 K (20 °C), respectively, and yearly average humidity ratio is calculated as 0.671 kg (water)/kg (air) and specific humidity is taken as 0.098 (kg water vapor /kg dry air) which is determined by the psychrometric chart.

A psychrometric chart is a graph of the physical properties of moist air at a constant pressure (often equated to an elevation relative to sea level). The chart graphically expresses how various properties relate to each other, and is thus a graphical equation of state. The thermophysical properties found on most psychrometric charts are: dry-bulb temperature (DBT), wet-bulb temperature (WBT), relative humidity (RH), humidity ratio, specific enthalpy, specific volume [19].

4. Results and discussions

The ambient conditions during November 2007–September 2008 and some performance data taken from the WTPPs are listed in Table 1. Measured average wind speed, production hours, product energy are given in table for each turbine. Production hour changes are caused because of the machine faults which occurred on the electric, electronic grid feed and mechanic control of the system. Product energy is measured between 76,502 and 168,376 (kW h) in stable operating conditions. If we compare the turbines, in spite of having the same operating hours product energy appears different for each, this is because of the different blowing air speed and some other conditions, meteorological conditions. This present

Table 1
Monthly measured performance parameters of WTTP (between November 2007 and September 2008 operating season) [13].

Months	Average ambient pressure (kPa)	Average ambient temperature (°C)	Average ambient relative humidity (%)	Average specific humidity ($kg_{water\ vapor}/kg_{dry\ air}$)	Turbine 1 Operation hours (h)	Turbine 1 Average wind speed (m/s)	Turbine 1 Energy product (kWh)	Turbine 2 Operation hours (h)	Turbine 2 Average wind speed (m/s)	Turbine 2 Energy product (kWh)	Turbine 3 Operation hours (h)	Turbine 3 Average wind speed (m/s)	Turbine 3 Energy product (kWh)
November 2007	101.640	14.4	74.35	0.0088	563	7.9	127,973	592	7.9	133,151	601	7.7	141,049
December 2007	101.780	10.4	73.26	0.0083	471	7.4	92,775	649	8.2	140,439	677	8	151,368
January 2008	102.230	8.4	68.29	0.008	654	7	122,896	631	7.2	116,099	646	7.2	115,958
February 2008	102.320	9.3	71.79	0.0085	524	7.4	116,661	517	7.9	116,654	503	7.8	108,279
March 2008	101.326	18.4	73.13	0.0076	662	8.6	168,376	675	9	172,904	695	9	181,894
April 2008	101.340	16.7	69.60	0.009	612	6.9	114,976	620	7.3	117,660	629	7.2	121,653
May 2008	101.350	19.8	63.39	0.011	632	6.1	76,502	659	6.6	82,727	659	6.3	84,053
June 2008	101.090	24.7	62.30	0.013	624	7.1	102,236	664	7.6	111,911	628	7.4	105,206
July 2008	101.105	26.0	59.16	0.0124	664	7.9	151,661	671	8.4	153,784	671	8.3	142,473
August 2008	101.005	26.6	62.39	0.0134	656	7.7	133,514	698	8.2	142,264	697	8.1	135,520
September 2008	101.140	22.8	64.67	0.0128	594	6.7	94,130	599	7.1	96,668	568	7	91,249

study concerns about the effects of these meteorological variables.

Fig. 1 exhibits the effects of both temperature and air density. We know that if ambient temperature increases, air density will decreases. In this study we analyzed that direct temperature effects on exergetic performance of wind turbine. In Fig. 1, there occurs 5 °C rise of temperatures for the exergetic evaluation due to the incorporation of the WTPP as compared to the temperatures. The effects of the air temperature of the WTPP on the monthly variations of the exergy efficiency have been depicted in Fig. 1. From the figure, it is seen that an increase temperature causes an increase of the exergy. This relation is used in the formulation. As seen in, while temperature differs from 268.15 K to 308.15 K, exergy efficiency increases from 23% to 27%. It means that exergy efficiency of wind turbines are direct affected ambient conditions.

In Fig. 2, numerical evaluation of relation between ambient pressure and exergy efficiency of wind turbines. To observe the effect of pressure, ΔP is changed from 100 to 1100 (Pa) in the formula. As can be seen from the figure, effects of the ΔP, pressure difference between inlet and outlet of the turbine, while ΔP increases, exergy efficiency decreases. It is discussed for different wind speeds, and obtained that lower wind velocities have higher exergy efficiencies than higher blowing wind velocities in same ΔP values.

And in Fig. 3, we represent the effect of specific humidity on exergy efficiency for different wind speeds. We take humidity values as specific humidity by the psychrometric chart for $P = 1$ atm. From the Fig. 3, there occurs 0.14 ($kg_{water\ vapor}/kg_{dry\ air}$) rise of specific humidity in ambient conditions, exergy efficiency decreases. In addition, lower wind velocities have higher exergy efficiencies than higher blowing wind velocities in same specific humidity.

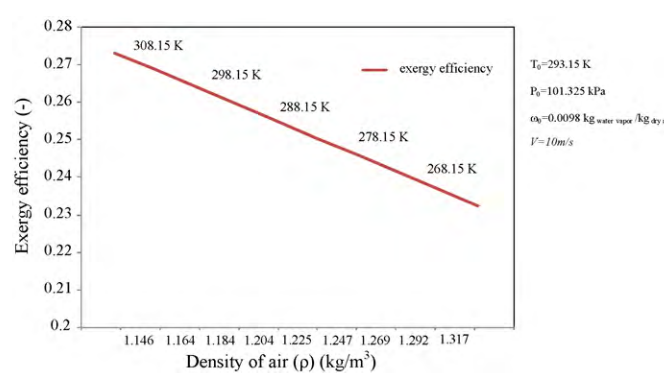

Fig. 1. Exergy efficiency-air density graph.

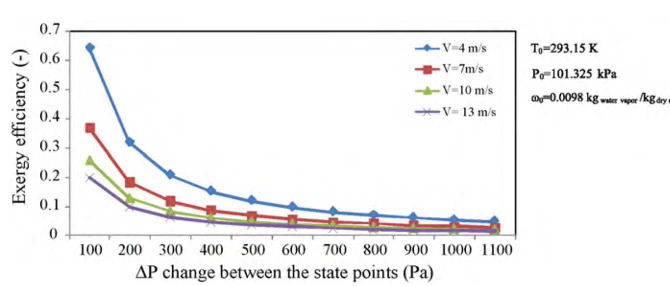

Fig. 2. Exergy efficiency-ΔP change between the inlet and outlet of the turbine at different wind speeds.

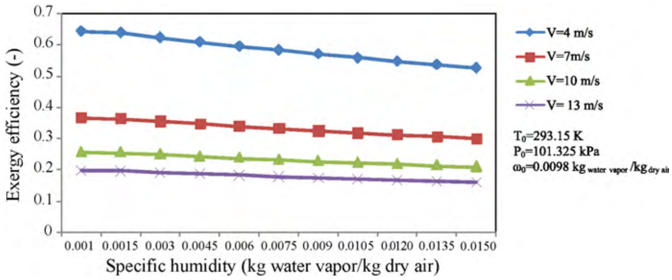

Fig. 3. Change of exergy efficiency by specific humidity at different wind speed.

5. Conclusions

The results obtained during the month of November 2007 till September 2008 were given and discussed. We can extract some concluding remarks from this study as follows:

- Depending on temperature, exergy efficiencies change between 23% and 27%.
- When ΔP and humidity increase, exergy efficiency is obtained decreasing.
- According to these results exergy analysis indicates that while planning WTTPs, meteorological variables must be taken into account.
- It is well known that, exergy rate of blowing air changes at different temperature and humidity values (e.g. [7,20]). In this study, it is obtained that exergy efficiency of blowing air changes at different temperature and humidity values.

Acknowledgements

The authors gratefully acknowledge the support provided for this work by Demirer Holding Inc. and personal support by its general manager, Mr. Erol Demirer. This study would not have been possible without the cooperation and assistance of the personnel at the Turkish State Meteorological Service.

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